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AUTHOR(S):

Qureshi, Ali Gul; Taniguchi, Eiichi; Yamada, Tadashi

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A microsimulation based analysis of exact solution of dynamic vehicle routing with soft time windows

Ali Gul Qureshi[a*], Eiichi Taniguchi[a], Tadashi Yamada[a]

[a]*Department of Urban Management, Kyoto University, Nishikyo-ku, Kyoto, 615-8540, Japan*

Abstract

This paper presents a microsimulation-based evaluation of an exact solution approach for the soft time windows variant of the Vehicle Routing Problem (VRP) that also considers penalties on the late arrival. The exact solution approach of the Dynamic Vehicle Routing and scheduling Problem with Soft Time Windows (D-VRPSTW) is based on the column generation (Dantzig-Wolfe decomposition) scheme; whereas VISSIM has been used to simulate the traffic network under normal as well as under traffic incident conditions. Evaluations shows that the D-VRPSTW helps in avoiding additional cost as well as lateness for the freight carriers, caused due to an unexpected change in travel times along the roads.

Keywords: City logistics; vehicle routing; soft time windows; microsimulation

1. Introduction

Almost all of the intra-urban frieght movement (both pickup and deliveries) is carried out by trucks and/or vans; for example in Tokyo, Japan, the share of road-based transport is about 99.4% of the total intra-urban freight movement (Bureau of Industrial and Labor Affairs in Tokyo Metropolitan Government, 2009). Door to door service industries such as home applience or utilities repair services, are also considered in the broader defination of the urban logistics. Traffic congestion, noise, vibrations, generation of NOx, SPM, CO_2 and other environmental problems, crashes, loading and unloading on the street side are typical problems caused by the road-based freight transport in urban areas. With time, there

[*] Corresponding author. Tel.: +81-75-3833422; fax: +81-75-9503800.
E-mail address: aligul@kiban.kuciv.kyoto-u.ac.jp

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has been some advancements in the logistics operations, such as the introduction of time windows, either by the customers/shippers (to improve logistics reliability) or by the administrators (specially in city centers, to improve traffic conditions, safety and environment). Such advancements put extra pressures on freight carriers by constraining their operation schedule (or their scheduling horizon) in this era of business competitiveness. An unexpected change in traffic situation (for example in case of a traffic incident) may significantly affect the optimized routes in these conditions leading to extra costs and delays, which may affect already slim profits as well as it may tarnish the reliability of a freight carrier. Therefore, the importance of bi-lateral communication between the truck drivers and the logistics-operations control unit of a company is increased, so as the importance of re-optimization of routes. These conditions leads to the definition of the Dynamic Vehicle Routing and scheduling Problem with Time Windows (D-VRPTW) in the field of city logistics.

The D-VRPTW is an extension of the Vehicle Routing and scheduling Problem with Time Windows (VRPTW), which is a typical route optimization technique employed in city logistics (Taniguchi *et al.,* 2001). Usually, the time windows [a_i, b_i] are treated as stringent constraints on delivery time, i.e. a vehicle has to wait until a_i if it arrives earlier than the start of the time window and delivery is not possible if it is delayed and arrives after the close of the time window (b_i). City logistics focuses on practical logistics problems, which are often set in soft time windows environment where late deliveries (w.r.t. time windows [a_i, b_i]) are possible at some penalty cost; this scenario is modeled using the Vehicle Routing and scheduling Problem with Soft Time Windows (VRPSTW). A routing system, in which complete or a part of input information (such as number and location of customers or travel time on arcs) is not available to the decision maker at the start but it is revealed during the scheduling horizon (day of operation), and in which the decision maker *reacts* to this new information by evoking some sort of *re-optimization* mechanism is defined as the D-VRPTW (Psaraftis, 1995). Considering the soft time windows in the D-VRPTW results in the Dynamic Vehicle Routing and scheduling Problem with Time Windows (D-VRPTW), which is the topic of this research.

There exists a significant body of literature on the dynamic customers case of the D-VRPTW; however, the literature on the D-VRPTW with dynamic travel time is scant with no attempt at exact approaches (for details please refer to the next section i.e., the literature review). This perhaps, is because a successful implementation of a routing system with dynamic travel times, is a very difficult task, which requires integration of data from various sources such as city traffic units and the logistics firms (Taniguchi *et al.,* 2001). With the introduction of the Intelligent Transportation Systems (ITS) such as the Vehicle Information and Communication System (VICS) in Japan, it is possible to collect, deliver and store such dynamic travel times on a link. Such type of ITS applications has somewhat eased the problem of the availability of dynamic travel time data, yet the use of this source is limited in city logistics-related research due to issues of accessibility and completeness (network coverage). In cases where the actual traffic data is not available, traffic simulation can be used to obtain useful data. For example, traffic microsimulation has been used in evaluations of ITS schemes (Ben-akiva *et al.*, 1997), Electronic Toll Collection (ETC) systems (Burris and Hildebrand, 1996) and so on; a comprehensive list of traffic microsimulation uses in transportation-related researches can be found in Liu *et al.* (2006).

This paper presents an evaluation of a column generation-based exact solution approach for the D-VRPSTW developed for the dynamic travel times case (Qureshi *et al.*, 2011). The travel time data is obtained for a test network under normal and under a traffic incident conditions using a microsimulation software, VISSIM. The travel time is updated whenever a dynamic traffic event occurs (such as a traffic incident), based on this updated travel time, the routes (for all vehicles) are re-optimized for the remaining part of the scheduling horizon. A comparative study of the static version of the VRPSTW with the D-VRPSTW shows that the latter minimizes the additional cost as well as the lateness in deliveries under an unexpected change in travel times along the roads.

2. Literature review

The objective of city logistics is to optimize the urban freight movement with respect to the public and private costs and benefits (Thompson and Taniguchi, 2001). Optimal location of logistics terminals (Yamada *et al.*, 2001) and cooperative delivery systems (Qureshi and Hanaoka, 2005) are some of the city logistics' schemes, aimed at the mitigation of the typical problems related to the urban freight transport mentioned in the previous section. Apart from its use as a typical route optimization tool, the VRPSTW is also used in evaluation of various city logistics schemes (Taniguchi and Heijden, 2000). Bulk of the research targeting the soft time windows is in heuristics domain such as local search heuristics (Hashimoto *et al.,* 2006), Tabu search (Duin *et al.,* 2007) and heuristics presented by Balakrishnan (1993) based on the nearest neighbor, Clarke-Wright savings and space-time rules. Particularly, genetic algorithms (GA) -based heuristics have been abundantly used in solving complex and close to real life VRPSTW instances in city logistics; for example, Taniguchi and Heijden (2000) used GA solutions of the VRPSTW to evaluate many city logistics measures such as cooperative delivery systems (CDS) and load factor control. Yamada *et al.* (2004) used a GA approach for the Probabilistic VRPSTW (VRPSTW-P) that incorporates the uncertainties of travel times on a road network to study the travel time reliability of a road network. Utilizing the VICS (Vehicle Identification and Communication System) data and the data from 66 days operation of probe pickup/delivery trucks, Ando and Taniguchi (2007) have applied the VRPSTW-P and its GA solution to an actual delivery system in Osaka, Japan. Qureshi *et al.* (2008) presented a hybrid genetic algorithm embedded in the flexible framework of the column generation scheme in an effort to reduce the computation time of the VRPSTW heuristics solution.

Earlier researches on exact solutions incorporating soft time windows have been focused on the schedule optimization of a given fixed path considering linear (Sexton and Bodin, 1985) and/or generalized convex penalty functions (Dumas *et al.,* 1990). On the other hand, many efficient exact solution approaches were developed for the hard time windows variant of VRPTW based on column generation (for example, Desrochers *et al.,* 1992; Kohl *et al.*, 1997; Feillet *et al.,* 2004; Irnich and Villeneuve, 2006). On the same lines, Tagmouti *et al.* (2007) have presented an arc routing problem with soft time windows, where vehicles are not allowed to wait along their routes. In their column generation scheme, they have used a modified labelling algorithm for the Shortest Path Problem with Time Windows and Time Costs (SPPTWTC) subproblem earlier given by Ioachim *et al.* (1998). The vehicle arrival pattern has been represented by a continuous variable resulting in very high computation times and limited the maximum size of problem solved to 40 customers. Qureshi *et al.* (2009) developed a column generation based exact solution approach for the VRPSTW and efficiently solved instances up to 50 customers under various soft time windows settings. Recently, Qureshi *et al.* (2011) extended it to incorporate the dynamic travel times and solve the D-VRPSTW.

It was observed in an earlier literature review (Qureshi, 2009) that there exists some noteworthy research, done in heuristic approaches for the D-VRPSTW to deal with the dynamic nature of the real life logistics operations. Among these researchers, the dynamic customers case of the D-VRPTW is the subject of majority of the researches (for example see, Larsen, 2001; Chen and Xu, 2006; Branchini *et al.*, 2009); whereas, the dynamic travel time case of the D-VRPTW has received a limited attention. Flieschmann *et al.* (2004) have used data from an ITS implemented in Berlin, Germany, named as LISB, which provides the travel time data on links for every 5 minutes slot. Taniguchi and Shimamoto (2004) have used a macro-simulation scheme to generate the dynamic travel time data for a theoretical test network. There has been some other macro-simulation applications with the VRPTW, for example Taniguchi and Heijden (2000) used a BOX model by Fuji *et al.* (1994) to evaluate environmental impacts of cooperative delivery system, load factor control and other city logistics schemes. To evaluate the effects of D-VRPSTW, Taniguchi and Yamada (2002) used a hybrid macroscopic/microscopic dynamic traffic simulation, in which vehicles can search for a shortest path along each node of their travel based on variable travel times. Macrosimulation is a useful source of dynamic travel time data, however, it does not depict the actual situation of the traffic on roads, specially the lane change, cooperative driving, queuing at signals, turning movements and the travel time required for all such details of traffic stream. Therefore, we used VISSIM, a microsimulation software to generate the dynamic travel time data that incorporate all before-mentioned components of the traffic flow. It becomes even more relevant to use microsimulation if the deliveries in the city center are being considered, which is the case of this city logistics-related study as well. The VISSIM has been used in variety of transportation-related researches, for example, in analysis of freeway congestion (Gomes *et al.*, 2004), in environmental evaluations of infrastructures (Noland and Quddus, 2006), in evaluations of travel demand management (TDM) schemes (Zao *et al.*, 2010) and so on. All research works mentioned in this section, for the DVRPSTW, with or without macrosimulation have adopted heuristics approaches. The heuristic techniques are sometimes faster and easily implemented than exact solutions, yet they do not guarantee to identify the exact solution or state how close to the exact solution a particular feasible solution is (Thompson and Van Duin, 2003). On the other hand the recently developed exact solution technique for the D-VRPSTW with dynamic travel times in Qureshi *et al.* (2011) was tested on arbitrary values of dynamic travel time using Solomon's benchmark instance (1987). Therefore, this research adopts a microsimulation to imitate actual traffic situation under a traffic incident case in a city center in order to strengthen the evaluations of the exact solution approach for the D-VRPSTW presented in Qureshi *et al.* (2011).

3. The dynamic VRPSTW

The Dynamic Vehicle Routing and scheduling Problem with Soft Time Windows (D-VRPSTW) is initially defined on a directed graph $G = (V, A)$. The vertex set V includes the depot vertex 0 and set of customers $C = \{1, 2, . . ., n\}$. The arc set A consists of all feasible arcs (i, j), $i, j \in V$. Initial values of cost c_{ij} as well as time t_{ij} are associated with each arc $(i, j) \in A$, based on some average travel time data (say daily average). Time t_{ij} includes the travel time on arc (i, j) and the service time at vertex i, and a fixed vehicle utilization cost is added to all outgoing arcs from the depot, i.e. in c_{0j}, $j \in C$. A set of identical vehicles (represented by K) with capacity q stationed at the depot, is available to service customers' demands at the start of the scheduling horizon. With every vertex of V there is an associated demand d_i, with $d_0 = 0$. The D-VRPSTW is modeled using the *rolling horizon* scheme, in which the complete scheduling horizon is divided into various time slots, each representing a time-based scenario. The time slots are marked with combination of *vehicle-based events* and *dynamic change-based events*, which means a new time slot is initiated as soon as a dynamic change is anticipated in the network (such as occurrence of a traffic incident) and the subsequent arrival of any of the vehicles to the next customer on its route. With no diversion allowed, the locations of all vehicles and their times of availability are forecasted depending on their current activity. For example, a vehicle traveling towards a customer would be available after serving the demand of that particular customer. The graph G is then updated showing vehicle locations along with all customers except those which are either serviced or are the first customers of an en-route vehicle. The arcs in the new graph G contain the updated travel times, therefore, planned routes would be based on these updated travel time values. It may be noted that, nodes other than depot, which contain a vehicle resource leads to a multi depots problem with heterogeneous vehicles because the residual capacity of each vehicle available at a virtual depot (i.e. the customer node containing a vehicle resource) is different. Fig. 1, shows the flow chart of the complete column generation based algorithm for the D-VRPSTW; for details please refer to Qureshi *et al.* (2011).

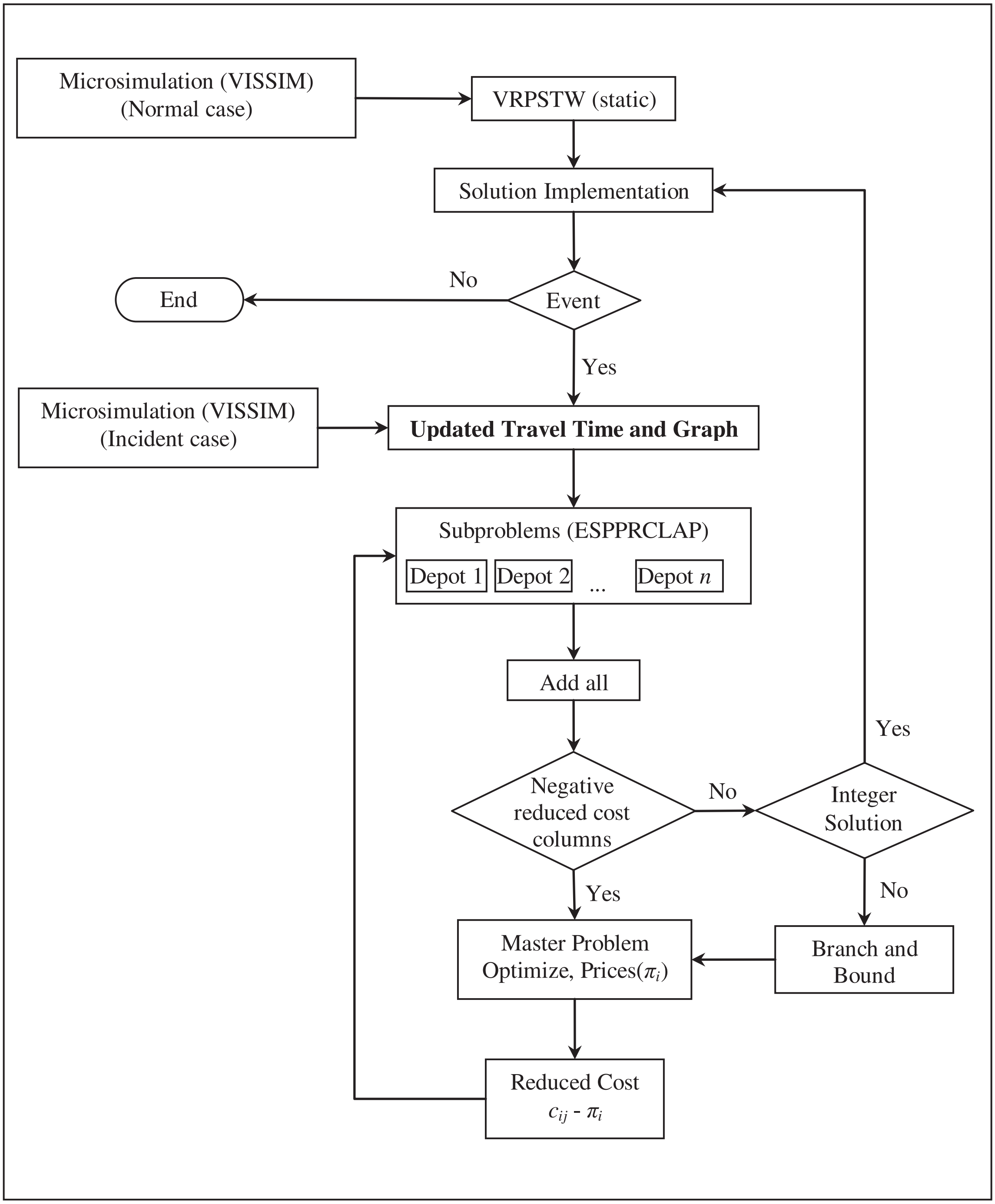
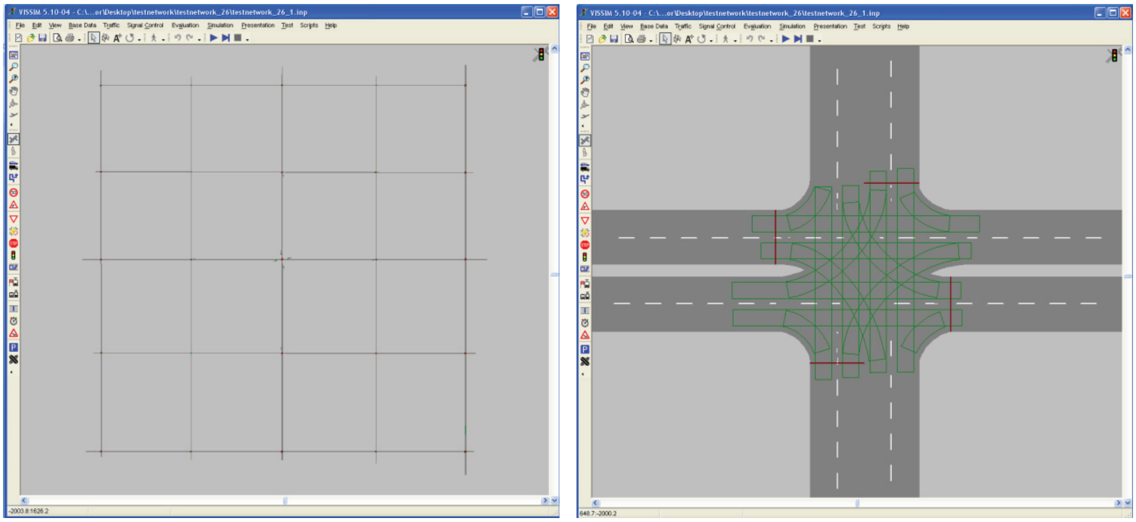


Fig. 1. Flow chart of column generation-based algorithm for the D-VRPSTW

4. Microsimulation-based test instance and the test scenario

Unlike the classical VRPTW, which has a comprehensive database of benchmark test instances proposed by Solomon (1987), no benchmark instance is available for the D-VRPSTW owning to its dynamic nature. Moreover, the Solomon benchmark instances are based on Euclidean distances, therefore, their arbitrarily modification with respect to travel time on disjoint the arcs represents a very unrealistic situation. In order to mimic the actual traffic situation under normal and incident cases, a microsimulation was developed in VISSIM of a test network (Fig. 2(a)) that contains two types of roads viz. major roads consisted of two lanes in each direction and the minor roads of one lane in each direction. For simple and clear representation a schematic diagram of the test network is shown in Fig. 3, whereas the actual VISSIM network contains the details such as turning movements, signals, vehicle inputs and their turning decisions as shown in Fig. 2(b) for the central node (customer no. 13 in Fig. 3).

The microsimulation covers approximately an area of 8 x 8 square kilometer with five different vehicle classes, viz. passenger car, bus, heavy vehicles (trucks), large motorcycle (with same maximum speed as cars, buses and trucks, i.e. 50 km/h) and light motorcycles (with maximum speed of 30 km/h). The traffic was generated using stochastic options in VISSIM, with varying traffic volume in each hour of the microsimulation. In microsimulation terms, the developed microsimulation was static in nature as the predefined percentages were allocated for different turning directions at intersections, regardless the situation on downstream links. To obtain a test instance for the D-VRPSTW, the time windows and the demand data of the first 24 customers of the Solomon's benchmark instance R101-100 were taken, whereas their locations were re-defined on the test network as shown in the Fig. 3. The depot is located at node one and nodes 2-25 show the customers. This remoulded instance was named as R101-24-D-VRPSTW. The scheduling horizon of the R101-24-D-VRPSTW instance is same as the Solomon's R101-100 instance, i.e. [0, 230], which represents the time windows at the depot node. A service time of 10 units is required at each customer to service its demand. Here we consider all time units as minutes. To obtain the travel time data both in normal and dynamic conditions (traffic instance case) by running five hour microsimulations, the first hour was considered as the warm up time.



(a) (b)

Fig. 2. Test network in VISSIM

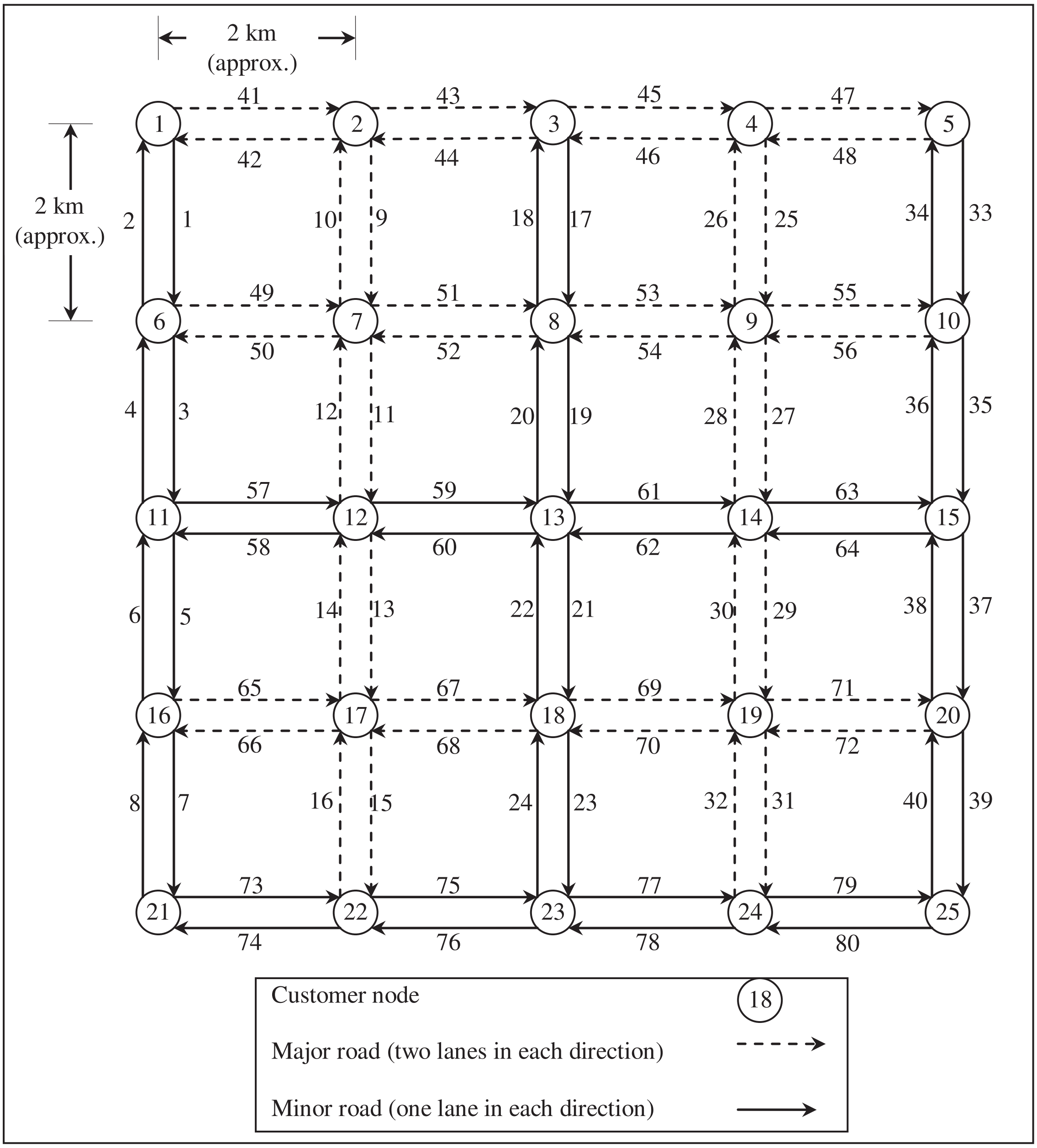


Fig. 3. The D-VRPSTW test instance

The exact VRPSTW (static) solution of the R101-24-D-VRPSTW with $b_i' - b_i = 10$ minutes for all $i \in C$, results in four vehicle routes as shown in Fig. 4. The exact static solution is based on the average travel times, under normal conditions for the last four hours of the microsimulation. In order to evaluate the performance of the D-VRPSTW and to show its advantage, a dynamic event of traffic incident was created at the link numbered 40 (Figure 3) starting at 60 minutes after the start of operations, i.e. after 2 hours of microsimulation, referred as "event time" hereafter in this manuscript. Two reduced speed areas (of 100 m length) were created on both lanes of this link with reduced speeds (approx. 2km/hr) for one hour. In the dynamic case, the new travel times (average travel time during the incident hour) were used along all links of the test network. It is important to consider that the link number 40 may not only be the shortest path (under normal conditions) from customer 25 to customer 20 but it may also be a part of many other shortest paths, for example from customer 24 to customer 20, which is the case in the initial static VRPSTW solution shown in Figure 4. Furthermore, a traffic incident on link number 40 may also impact the travel time on other links, for example at link number 79 (due to queuing effect) or at links numbered 38 and 72 (which receive traffic from link number 40). Therefore the affect of the dynamic event may be much wider than the area directly affected by the incident. This situation also emphasizes the need of a microsimulation-based test instance for the dynamic case instead of simple adoption of the Solomon's benchmark instance by changing the travel time on any arc (*i, j*) of the Euclidean graph *G* used in the Solomon's benchmark instances. For results on such simply adopted Solomon's benchmark instances, please refer to Qureshi *et al.* (2011).

Route 1: 1 - 3 - 13 - 8 - 9 - 10 - 5 - 2 - 1
Route 2: 1 - 15 - 24 - 20 - 19 - 4 - 14 - 1
Route 3: 1 - 16 - 12 - 7 - 11 - 18 - 1
Route 4: 1 - 6 - 22 - 17 - 23 - 21 - 25 - 1

Fig. 4. The initial static VRPSTW solution of the R101-24-D-VRPSTW test instance

Table 1 gives some details of the static VRPSTW solution (shown in Figure 5) at the event time such as the ready time (time of availability) of each vehicle at the next customer on its route and the residual capacity of the vehicle (other details such as cost etc. are given in next section). At every event in the dynamic case, it is assumed that additional vehicles are available at the origin depot (node 1 in Figure 3) as well; during the re-optimization a new route can start from the origin depot if the solution with additional vehicle results in the least cost. It may be noted that by the event time all vehicles of the initial static solution has already departed for the depot.

Table 1. Routes' details of the initial static VRPSTW solution of the R101-24-D-VRPSTW test instance

Vehicle	1	2	3	4
First Customer	13	24	16	22
Residual Capacity	174	151	192	163
Ready Time	68.4	68	61	62

5. Results and discussions

Both the static and the dynamic version of the column generation-based exact algorithm for the VRPSTW were implemented in MATLAB, and computations were carried out on a computer with 2.67 GHz Intel Core i7 CPU with 6 GB of RAM. In this study, the vehicle operation cost (VOC) of 14.02 yen/minute is taken; while the fixed cost for a vehicle is set to 10417.5 yen. The unit late arrival penalty is taken as five times that of the VOC. These unit cost values are based on a survey of Japanese logistics companies and most commonly used in the city logistics-related literature (for example, see Taniguchi *et* *al.*, 2001; Yamada *et al.*, 2004; Ando and Taniguchi, 2006; Duin *et al.*, 2007). Figure 5 shows the re-optimized routes obtained in the D-VRPSTW exact solution for the R101-24-D-VRPSTW test instance. The virtual depots are shown in bold face and the highlighted part of the route is the result of the D-VRPSTW, whereas, customers to the left of the virtual depots (including themselves) are already served customers at the event time. Considering the complete graph *G* of the initial static VRPSTW, the link number 40 was part of the arc (24, 20). It is interesting to observe that the same arc (i.e. (24, 20)) is being traversed in the D-VRPSTW solution as well; however, in the dynamic case, the new path along the arc (24, 20) of the graph *G* (consisting of links numbered 32 and 72) avoids the part of network affected by the traffic incident. It can be noted that in the dynamic case, almost all routes are different from the static case in order to optimize the overall solution.

Route 1: 1 - 3 - **13** - 8 - 9 - 4 - 5 - 14 - 1
Route 2: 1 - 15 - **24** - 20 - 10 - 25 - 1
Route 3: 1 - **16** - 12 - 7 - 11 - 2 - 1
Route 4: 1 - 6 - **22** - 17 - 19 - 23 - 21 - 18 - 1

Fig. 5. The D-VRPSTW solution of the R101-24-D-VRPSTW test instance

Table 2. The D-VRPSTW and the VRPSTW (static) exact solutions of the R101-24-D-VRPSTW test instance

Case	Solutions	No. of Veh.	Cost (Yen)	Difference from initial Solution (Yen)	Late Arrival Time (minutes)	Difference from initial Solution (minutes)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Case 1	VRPSTW (Static)	4	47289	-	16	-
Case 2	VRPSTW (Static, no change)	5	59567	12278	30.3	14.3
Case 3	VRPSTW (Static, with path change b/w customers 24 and 20)	4	47450	161	18.1	2.1
Case 4	D-VRPSTW	4	47214	-75	15.4	-0.6
Net benefit of D-VRPSTW from Case 2				12353		
Net benefit of D-VRPSTW from Case 3				236		

The Table 2 gives details of the exact solutions of the D-VRPSTW and the initial static VRPSTW (shown in Figure 4) under different case considerations. Case 1 and Case 4 represent the initial static VRPSTW solution and the D-VRPSTW solution, respectively. Case 2 shows the application of the static VRPSTW solution even after incident occurred at link number 40 (i.e. Static, no change). Here we have considered a simple strategy that calls back the vehicle, if it becomes certain that the next customer will become infeasible (due to lateness beyond the permitted $b_i' - b_i = 10$ minutes) and instead a new vehicle is dispatched to cover the remaining route of the called back vehicle. For example, due to the incident on link number 40, it becomes infeasible to service customer 19 after visiting customer 20 in the static VRPSTW solution, and therefore the vehicle of route 2 returns back to the depot after visiting customer 20 and a new vehicle is dispatched to cover the remaining portion of route 2 starting from the customer number 19. Case 3 represents a scenario when the path along the arc (24, 20) is changed avoiding the link number 40. In this case, an alternative path from customer number 24 to customer number 20 (obtained during the dynamic case) was used, whereas no changes were made to the order of customers on the route number 2 of the static VRPSTW solution.

In Table 2, Col. (3) shows the number of vehicle routes in each solution; whereas, Col.(4) and Col.(6) gives the total cost and the late arrival time (LAT) in these solutions. Differences in cost and late arrival time between the initial static solution and the static and dynamic solutions under different cases are reported in Col. (5) and Col. (7), respectively. All solutions contain four vehicle routes, except the static solution in case 3, which contains an additional vehicle due to the feasibility condition described in case 3. It can be observed that if we continue to use the static VRPSTW solution under the dynamic travel time scenarios (i.e. both in cases 2 and case 3) high additional costs (Col. (5)) as well as additional delays (Col. (7)) are incurred as compared to the D-VRPSTW. Additional lateness may tarnish the reliability of the freight carrier as well resulting in further loss of business. On the other hand, the D-VRPSTW solution resulted in reduced cost and less delays in our application; this may be the result of different distribution of traffic in the road network due to inherited stochasticity of the microsimulation software VISSIM or due to the incident on link number 40. However, this result cannot be expressed as a general trend, nonetheless it is expected that the D-VRPSTW would always perform better than the static VRPSTW solutions and/or its applications with some simple recourses as considered in cases 2 and 3. As compared to the case 3, use of the D-VRPSTW saves about 236 Yen only but this case itself can be considered as partly dynamic due to change of the path; whereas, the savings as compared to in case 2 are more significant (12353 Yen) due to the fact that the D-VRPSTW exact approach efficiently re-optimizes the whole solution and no additional vehicle is used. It is also significant to note that the D-VRPSTW exact solution was obtained in approximately two (02) seconds, whereas the Dijkstra algorithm took an additional 0.18 seconds (on average). This shows the efficiency of the column generation-based exact solution approach for the D-VRPSTW, specially for these small problems; however, it is expected that the computation time would grow rapidly for larger instance (say for 50 customer instances) as noted in the exact solution approach for the static VRPSTW (Qureshi *et al.*, 2009).

6. Conclusion

In urban areas traffic incident and other situations may lead to unexpected changes in traffic conditions resulting in the dynamic travel times on the roads. From the city logistics viewpoint, these unexpected changes in the travel time may affect the distribution or pick-up routes of the delivery vehicles resulting in additional costs and in unexpected long delays if the routing is fixed and based on any static value of travel time (such as the average travel time). The Dynamic Vehicle Routing Problem with Soft Time Windows (D-VRPSTW) can be used to counter this situation. Results presented on a microsimulations-based test instance under dynamic travel time condition proved this statement in this study. The future research includes the use of the developed exact method for the D-VRPSTW in evaluating city logistics policies for practical logistics instances based on real road network data.

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